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# A Search for Fast Gamma Ray Pulsars with OSSE

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## ABSTRACT

Pulsar mode data from the Oriented Scintillation Spectrometer Experiment (OSSE) onboard the *Compton Gamma Ray Observatory*, with time resolution between 125 $\mu$s and 8 ms, have been analyzed for the presence of short period $\gamma$-ray pulsations. Observations of known point sources (including SN 1987A, SN 1993J, GRO J0422+32, and several pulsars) and of regions where high densities of pulsars are expected (including the Galactic Center, the Galactic plane and arms, and the Large Magellanic Cloud) are included in the study. Both isolated pulsars and pulsars in close binary systems are searched for; in the latter case, the quadratic coherence recovery technique is used to correct for broadening of the pulsar signal from orbital motion.

No new $\gamma$-ray pulsars have been detected. Upper limits on the pulsed $\gamma$-ray flux from isolated pulsars in the 50–210 keV energy range of OSSE are between $0.2 \times 10^{-3}$ and $2.0 \times 10^{-3}$ photons s$^{-1}$ cm$^{-2}$ for pulse periods between 250 $\mu$s and 0.5 s. Upper limits on the pulsed flux from binary pulsars are between $1.5 \times 10^{-3}$ and $6.4 \times 10^{-3}$ photons s$^{-1}$ cm$^{-2}$ for the same energy band and pulse period range. We estimate that, in the Galaxy, there are fewer than $\sim$125 isolate pulsars similar to PSR B1509-58 with radiation peaks in the OSSE band but undetected in the radio and X-ray bands.

*Subject headings:* Gamma Rays: Observations — Methods: Data Analysis — Pulsars: General

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## 1. Introduction

The study of periodic, quasiperiodic, and aperiodic variability in cosmic sources is a crucial aspect of high energy astrophysics. The detection and study of temporal signatures, in particular coherent pulsations from pulsars, provides information on the physical nature of X-ray and $\gamma$-ray sources. For instance, the periodic change in the phase of pulsed emission is necessary to determine the mass of a pulsar in a binary system (Joss & Rappaport 1976), and the period and period derivative of an isolated pulsar can be used to constrain the pulsar's age and magnetic field (Taylor & Stinebring 1986; Bhattacharya & van den Heuvel 1991).

Gamma-rays are expected, at some luminosity, from all known (and at least one hypothesized) classes of pulsars. In the outer gap model for rotation powered pulsars (Cheng, Ho, & Ruderman 1986a,b), the pulsar's primary emission is $\gamma$-rays which are then converted into longer wavelength radiation through a cascade of pair creation and destruction in the neutron star's magnetic field. The $\gamma$-ray luminosity and the ratio of $\gamma$-ray to radio flux depend on the magnitude and inclination of the magnetic field as well as the spin period, with higher $\gamma$-ray luminosity for more rapidly spinning pulsars (Ho 1993; Ruderman et al. 1993). The discovery that the bright $\gamma$-ray source Geminga is a nearby pulsar (Halpern & Holt 1992; Bertsch et al. 1992) confirms that pulsars unknown by their radio, optical, or X-ray emission can be discovered through their $\gamma$-ray emission. Production of high energy $\gamma$-rays may also take place in binary systems where the companion's wind or atmosphere can confine the pulsar wind; acceleration of particles can take place in the resulting pulsar wind shock (Harding & Gaisser 1990). In a more speculative vein, Tavani (1991) proposes a class of currently unobserved "hidden" millisecond pulsars, completely engulfed by evaporated material from the irradiated companion star and therefore radio quiet, which nonetheless have significant, although not pulsed, high energy emission.

The launch of the *Compton Gamma Ray Observatory* (GRO) has increased the sensitivity for the detection of $\gamma$-ray pulsars by more than an order of magnitude. Predictions of the number and identity of pulsars which might be detectable with GRO instruments (Taylor 1989; Thompson & Kniffen 1989; Chiang & Romani 1992) are necessarily based on properties of known radio pulsars, and pulsed $\gamma$-ray emission has been detected by GRO from six pulsars (Ulmer 1994; Thompson 1994). Three of these $\gamma$-ray pulsars have been detected with OSSE: the Crab pulsar (Ulmer et al. 1994), the Vela pulsar (Strickman et al. 1993), and PSR B1509-58 (Ulmer et al. 1993; Matz et al. 1994). Considerable OSSE observing time was dedicated to observations of fifteen additional pulsars (Ulmer & Schroeder 1994a; Schroeder et al. 1994), including the three detected by the EGRET instrument on CGRO but not by OSSE.

The three pulsars detected by OSSE are all short period pulsars lying above the "death line" for an outer magnetosphere accelerator (Chen & Ruderman 1993). From both EGRET and OSSE observations, there is a good correlation between $\gamma$-ray luminosity and the dipole energy loss mechanism ($\dot{E} \propto B^2 P^{-4}$) (Ulmer & Schroeder 1994a). There is every expectation that fast (rapidly spinning) pulsars can be *discovered* through their pulsed $\gamma$-ray emission, and that the discovery of such systems can provide important information on the physical properties of pulsars in general. As an added bonus, periodic emission can be detected at fluxes well below the steady background, so sources whose phase-averaged emission would be undetectable in a single exposure can be revealed through their temporal signature.

We have undertaken a program to search for fast ($P < 0.5$ s) $\gamma$-ray pulsars in data obtained with the Oriented Scintillation Spectrometer Experiment (OSSE) instrument onboard GRO. As we describe in §2, OSSE data are well suited for enabling sensitive searches for short period pulsars. Our program is a piggy-back search for serendipitous discoveries — no new pointings have been made for this search. Rather we analyze data obtained during observations of regions where the density of pulsars is believed to be high, such as the spiral arms and plane of the Milky Way, the Galactic Center, and the Large Magellanic Cloud.

In our analysis, we have attempted to optimize the probability of detecting a fast pulsar. This requires different strategies for known pulsars, unknown isolated pulsars, and unknown binary pulsars (§3). Even with optimized algorithms, the CPU and memory requirements necessitated performing the bulk of the analysis on a CM-2/200 massively parallel supercomputer. The sensitivity of our searches for fast binary pulsars is generally limited by the signal-to-noise of the data rather than by the available computation time. So far we have detected no new $\gamma$-ray pulsars (§4).

In this paper, we describe our program and techniques. We also report results to date in the continuing search. We comment briefly on the implications of our non-detections (§5).

## 2. Instrumentation and Observations

All data were obtained with the Oriented Scintillation Spectrometer Experiment (OSSE) on the *Compton Gamma Ray Observatory* satellite. OSSE provides spectroscopic and photometric observations of $\gamma$-ray sources in the 50 keV to 10 MeV range. The instrument consists of four identical large-area NaI(Tl)-CsI(Na) phoswich detector systems, each of which is actively shielded by a NaI(Tl) annulus and passively collimated by a

tungsten slat collimator that defines a $3.8^\circ \times 11.4^\circ$ full-width at half-maximum (FWHM) $\gamma$-ray aperture. The total aperture area of the four detectors is 2620 cm$^2$, with an effective photopeak area at 511 keV of $\sim$2000 cm$^2$. The experiment has an energy resolution of 8.2% (54 keV) at 661 keV and 3.8% (0.23 MeV) at 6.13 MeV. A complete description of the OSSE instrument and experimental capabilities is given by Johnson et al. (1993). OSSE is well suited to fast pulsar searches, and the study of pulsed and steady-state emission from pulsars is one of OSSE's scientific objectives (Kurfess et al. 1989).

The OSSE instrument simultaneously collects spectral and high time-resolution (or pulsar mode) data. Spectral observations consist of a sequence of two-minute measurements of a source field alternated with two-minute offset-pointed measurements of background. The study reported here was conducted with pulsar mode data. OSSE's pulsar mode is highly programmable for maximum flexibility in meeting the scientific goals of any specific observation. Several energy bands can be included in the telemetry allocated to the pulsar data. Gamma ray events qualified as being in one of these energy bands are then processed in one of two modes, either time-tagged EBE (event-by-event) mode or binned RATE mode. In EBE mode, a maximum of $\sim$470 selected events per 2.048 s packet are time tagged with a precision of either 1 ms or 125 $\mu$s. Once the EBE buffer is full, no photons are recorded for the remainder of the 2.048 s interval. In RATE mode, selected events are binned into samples with selectable sample size between 4 ms and 512 ms. In a typical 4 ms RATE mode configuration, up to $\sim 10^4$ events s$^{-1}$ can be supported. The detected event rates include background events, which dominate source counts in most observations.

We have studied three classes of sources in our search for fast $\gamma$-ray pulsations. The first class contains known pulsars with no prior detection at $\gamma$-ray energies. The fast X-ray pulsars PSR B0540-693 ($P = 50.4$ ms) and PSR B1613-509 ($P = 69.3$ ms) are in this class. The second class contains known objects from which $\gamma$-ray pulsations might be expected, such as recent supernovae in the LMC (SN 1987A) and M81 (SN 1993J) and the X-ray nova GRO J0422+32 (Nova Per 1992). The third class contains previously unknown sources. We study these sources by searching for periodic emission from fields where we might expect a high density of pulsars. These fields include the nearby spiral arms in Carina and Cygnus, other Galactic plane fields, the Galactic Center, and the LMC.

In Table 1 we give an observation log of the OSSE data we have analyzed. It is necessary to assume a position in the sky for previously unknown sources in order to correct photon arrival times to the solar system barycenter. We have searched many OSSE observations for pulsars at multiple locations. In order to keep track of the data sets analyzed, we have given an arbitrary "observation ID" to each combination of an OSSE data set and a celestial position. These ID's are reported in the first column of Table 1.

We also give the target of the OSSE observation, the GRO viewing period, the viewing direction used for barycentric corrections (in Galactic and celestial coordinates), the energy range of accepted counts as determined by the pulse height discriminators, and the number of independently targetable OSSE detectors (out of 4 total) used in the observation.

## 3. Analysis Methods

There are many available algorithms that can be used to search for periodicities in time series data. The most computationally efficient of these have a fast Fourier transform (FFT) at their core. Pulsations are detected as peaks in the resulting power spectra. For a stable coherent pulsation, as one might expect from an isolated pulsar, the power spectrum from an FFT is sufficient to detect pulsed emission (§3.1). However, a pulsar in a binary system has its signal frequency modulated at the orbital period. This results in a loss of coherence, and the pulsed power is spread over many channels in the power spectrum. As millisecond radio and X-ray pulsars can be found in short period binaries, we reasonably expect $\gamma$-ray pulsars to also be found in binary systems. We must adopt some method of coherence recovery in order to maximize the sensitivity of our search to pulsations from such pulsars (§3.2).

### 3.1. Isolated Pulsars

For isolated pulsars, or pulsars in sufficiently wide orbits that there is no significant shift in frequency during the observation, we maximize the sensitivity of our power spectra to coherent pulsations by performing the largest FFT possible. If there is more data than can be transformed at once, or if there are large gaps in the data stream, then incoherent summation of all available power spectra is used to obtain the best sensitivity (van der Klis 1989).

The data contain a number of periodic but non-astrophysical signals produced by the instrument, the satellite, and the local environment. As GRO orbits the Earth, occultation of the source by the Earth breaks the data stream into segments of a few thousand seconds of source data followed by a gap lasting a few thousand seconds while the source is occulted. Slow variations in the detected count rate are caused by orbital background variations in OSSE data from one GRO orbit to the next. Quasi-regular data drop outs are caused by the passage of GRO through the South Atlantic Anamoly and, in observations made after the loss of the GRO on-board tape recorder in 1992 March, by gaps in the real-time telemetry

link through the Tracking and Data Relay Satellite System (TDRSS). Regular drop outs, with a 2 min period, are caused by OSSE's on-source/off-source rocking motion. In EBE mode, there is also a 2.048 s periodicity in the data due to zero filling data packets after the maximum number of counts ($\sim$470) allowed in each packet have been detected. The window function due to the packet filling, detector rocking, and data drop outs aliases the orbital background variations to give rise to low frequency noise and harmonics of the 2.048 s and 2 min periods. We have thus chosen to concentrate our search on periods shorter than 0.5 s.

We adopted two patterns of choosing transform length for isolated pulsars. In the first pattern, we transformed data separately for each GRO orbit and then incoherently summed the resulting power spectra. In this pattern, the time series contained primarily live data and relatively little "fill data" from when the target was occulted. These time series are typically 1024 s to 4096 s long. The second pattern consisted of transforming the longest data streams possible. Since occultation data are included, the target window is open less than 50% of the time during these data streams. This pattern was made possible during the later months of analysis, when the memory in the Connection Machine was upgraded to allow FFTs of up to 64 million data points (see §3.4). Simulations show that the second pattern provides more sensitivity to fast pulsars than the first pattern.

### 3.2. Binary Pulsars

Pulsars in binary systems will have their pulsations frequency modulated at the orbital period. If the parameters of the orbit are sufficiently well known, then the timing data can be corrected for motion of the source and an FFT will recover all of the pulsed power in a single channel of the power spectrum. However an FFT of uncorrected data from a binary pulsar will spread the pulsed power over many frequency channels. For high time resolution OSSE data and short binary periods ($\lesssim$ 12 hr), the signal is spread over many thousands of channels. In order to recover the pulsed power, trial orbital solutions are adopted prior to transforming.

It is computationally impractical to search the entire three dimensional phase space (orbital period $P_{\rm orb}$, projected semimajor axis $a_\perp$, orbital phase $\phi$) of candidate circular orbits (Wood et al. 1987). Fortunately it is not necessary if we use the quadratic coherence recovery technique of Wood et al. (1991; see also Hertz et al. 1990, Vaughan et al. 1994). As long as the duration of the data segment $T$ is small compared to the orbital period, $T \lesssim P_{\rm orb}/4\pi$, the arc of the orbit during the observation can be approximated with a parabola. A single parameter $\alpha$ ($\alpha \equiv 4a_\perp\pi^2\sin(\phi)/P_{\rm orb}^2$) can be used to define a quadratic time transform which completely recovers the pulsed power in a single frequency channel,

and the problem is reduced to a one dimensional search. The number of values of $\alpha$ which must be tried for a complete search, $N_\alpha$, scales as $N^{4/3}\tau^{-1/3}$, where a data segment consists of $N$ bins with time resolution $\tau$ so that $T = N\tau$ (Hertz et al. 1990). For our searches, $N_\alpha$ is between 53 and 6000.

We expect that $\gamma$-ray pulsars may be found in close binaries. For binary pulsar searches, we limited our searches to a single orbit's worth of data ($T = 2048$ s or $T = 4096$ s). Our search is therefore complete (to the quoted pulsed fraction limits) for pulsars with low mass companions ($M_{\rm comp} \lesssim 0.5{\rm M}_\odot$) in orbits with $P_{\rm orb} \gtrsim 7.1$ hr or $P_{\rm orb} \gtrsim 14.3$ hr, respectively. Pulsars in shorter orbits, and pulsars with high mass companions observed near quadrature, can be detected but only at higher pulsed fractions (Wood et al. 1991).

Note that the value of the quadratic parameter $\alpha$ that recovers pulsed power changes with orbital phase, and is thus different (in an *a priori* unknowable manner) from GRO orbit to orbit and from data segment to data segment. For binary searches we cannot incoherently sum power spectra to increase sensitivity; each GRO orbit's worth of data is a complete and independent search (see, however, Vaughan et al. 1994). In order to conserve computational resources, we search only a few orbits from each OSSE observation and thus sample several orbital phases of any binary pulsar observed. Assuming the pulsar is not transient, this is sufficient.

### 3.3. Statistical Significance

An OSSE binned data segment consists of $N$ bins with time resolution $\tau$ and segment duration $T = N\tau$. Typically, $\tau$ is 125 $\mu$s – 8 ms, $N$ is 250k – 64M, and $T$ ranges from a single orbit (1024 s) to 6 days (512k s). We use the binary notation that "k" is 1024 ($2^{10}$) and "M" is 1048576 ($2^{20}$). The average count rate is $R$ during the data segment, so that the number of photons is $N_{\rm ph} = RT$. We scale the data by $\sqrt{2/N_{\rm ph}}$ before taking the FFT. This is the power spectrum normalization of Leahy et al. (1983). With the Leahy normalization, Poisson noise has a value of 2 in the power spectrum. If appropriate, we incoherently sum $M$ normalized power spectra. We then search for a significant peak in the $N_{\rm trial}$ frequencies of the summed power spectrum. For a pulsar with a known period, $N_{\rm trial} = 1$, and for an isolated pulsar with no known period, $N_{\rm trial} = N/2$, the number of independent frequencies. (The number of unsearched frequencies less than the 2 Hz frequency minimum is negligible.) In a search for a binary pulsar, $N_{\rm trial} = N_\alpha N/4$ ; in the quadratic coherence recovery technique, frequency channels in power spectra with consecutive values of $\alpha$ are not independent because signals with different frequencies are spread out by different amounts in the power spectrum (Hertz et al. 1990; Wood et al. 1991).

We use the methods and notation of van der Klis (1989) to set $P_{\rm detect}$, the threshold normalized power that a pulsed signal must exceed in the summed power spectrum in order to be detected. We also wish to determine $A_{\rm UL}$, the upper limit to the rms variability (or pulsed fraction of the total source plus background count rate) when no pulsed signal is detected. Recently Vaughan et al. (1994) pointed out that the common practice (e.g., Leahy et al. 1983; van der Klis 1989; Wood et al. 1991) of assuming that the probability distribution of the total power detected and of the power due to noise are independent is incorrect when $M$ is small, say $M \lesssim 10$. We adopt here the methods of Vaughan et al. (1994) for determing $A_{\rm UL}$; the results presented in this paper supercede preliminary results (Hertz et al. 1991, 1993, 1994) where the incorrect assumption of independence was made for non-summed power spectra.

Let $Q(\chi^2|\nu_{\rm dof})$ be the probability that a random variable that is $\chi^2$-distributed with $\nu_{\rm dof}$ degrees of freedom exceeds a value of $\chi^2$. Then $P_{\rm detect}$ is given by

$$\epsilon = N_{\rm trial}\, Q(M P_{\rm detect}|2M) \tag{1}$$

where $1-\epsilon$ is the confidence level. If the maximum power detected does not exceed the detection threshold ($P_{\rm max} < P_{\rm detect}$), then the $1-\epsilon'$ confidence upper limit to the power of any coherent signal $P_{\rm UL}$ is given by

$$\epsilon' = 1 - e^{[-(P_{\rm max}+P_{\rm UL})/2]} \sum_{m=0}^{\infty} \sum_{k=0}^{m+M-1} \frac{P_{\rm max}^k\, P_{\rm UL}^m}{k!\, m!\, 2^{m+k}} \tag{2}$$

(Groth 1975; Vaughan et al. 1994). In an appendix, Vaughan et al. (1994) give a `FORTRAN` program for calculating $P_{\rm UL}$ as a function of $\epsilon'$, $M$, and $P_{\rm max}$; we have used their program. When $M \gtrsim 10$, the approximation that total power and noise are independent is acceptable. Under that assumption, van der Klis (1989) shows that

$$P_{\rm UL} = P_{\rm max} - P_{\rm noise} \tag{3}$$

where $P_{\rm noise}$ is given by

$$1 - \epsilon' = Q(M P_{\rm noise}|2M)\,. \tag{4}$$

We have used a 90% confidence limit, corresponding to $\epsilon = \epsilon' = 0.1$.

The pulsed fraction upper limit is then

$$A_{\rm UL} = C_{\rm dt} C_{\rm bin} \sqrt{\frac{P_{\rm UL}}{N_{\rm ph}}} \tag{5}$$

where $C_{\rm dt}$ is the correction due to dead time effects and $C_{\rm bin}$ is the correction due to finite binning effects. We emphasize that this is typically the pulsed fraction of the background

rate, since OSSE observations of weak or undetected sources are background limited. The pulsed flux upper limit is

$$F_{\rm UL} = \frac{A_{\rm UL} R}{A_{\rm eff}}\,, \tag{6}$$

where $A_{\rm eff}$ is the effective area of the OSSE detectors and $R$ is the average detected count rate, as before.

OSSE pulsar mode data have a dead time $\tau_{\rm dt}$ of $\sim$80 $\mu$s per event (Roberts 1992). Van der Klis (1989) gives the dead time correction as

$$C_{\rm dt} = \frac{1}{1 + R\,\tau_{\rm dt}(1 - R\,\tau_{\rm dt})^2}\,. \tag{7}$$

Note that the incident count rate,

$$R_{\rm inc} = \frac{R}{1 - R\,\tau_{\rm dt}}\,, \tag{8}$$

is greater than the detected count rate $R$. In high count rate EBE mode, these calculations are for the period before the 2.048 s buffer fills. The binning of data causes the power spectrum to be preferentially supressed at higher frequencies. The correction factor for a signal with frequency $\nu$ where the data have been binned with resolution $\tau$ is (Leahy et al. 1983)

$$C_{\rm bin} = \frac{\pi\nu\tau}{\sin(\pi\nu\tau)}\,. \tag{9}$$

This factor ranges from 1.0 at low frequencies to $\pi/2$ at the Nyquist frequency ($\nu_{\rm Nyq} = 1/(2\tau)$).

### 3.4. Implementation on the Connection Machine

Data are selected and prepared on the OSSE VAX cluster. For convenient portability across system architectures, data during a relevant time interval (typically one day), and for an appropriate set of detectors and energy windows, is reformatted so that each packet contains a header record with the requisite timing information (e.g., the solar-system barycenter vector) and a photon data record.

The data are transferred to the NRL Connection Machine Facility to be processed on the CM-2/200 (Hillis 1987). This project was begun using a CM-2. The Connection Machine CM-2 is a massively parallel computer with 16k processors organized into 512 nodes. Each node has its own FPA and memory. During FY92 the CM-2 received a memory upgrade (from 125 Mbyte to 2 Gbyte) to become a CM-200. The additional

memory increased the maximum FFT size from 4M to 64M. The CM-2/200 is served by a serial front end computer (a Sun 4/690) which reads and compiles programs, reads data from serial disks, and sends compiled code and data to the CM-2/200 for execution.

The data are read into the front end computer one packet at a time. Using the source direction (which may not be the instrument pointing direction), the time of each datum in each packet is corrected to the solar system barycenter. It is then placed into an array on the CM-2/200. If binary pulsars are being searched for, a parallel quadratic time transformation of the data is performed. Next an FFT is performed using the parallel algorithm of Hertz (1990) and the power spectrum is calculated. If multiple power spectra are to be incoherently summed, the data are held in CM-2/200 memory for the next power spectrum. Final power spectra are stored on a 10 Gbyte parallel disk array for further analysis. Parallel implementation is described in more detail in Hertz et al. (1990). Final power spectra are searched for the highest peaks, and these are compared to the detection threshold.

The entire software package has been thoroughly tested in previous searches for millisecond X-ray pulsations (Hertz et al. 1990; Wood et al. 1991; Hertz et al. 1992). We performed additional tests, especially on the transfer of OSSE data to the CM-2/200, by searching for periodicities in observations of the Crab pulsar and Her X-1. We successfully recovered both pulsars (Hertz et al. 1991).

## 4. Results

To date we have searched for fast pulsars in selected OSSE observations obtained during Phase 1 and Phase 2 of the GRO mission. We have detected no significant signals, other than in the test data sets, from either isolated or binary pulsars. In Tables 2 and 3 we give relevant properties of the observations, the analysis, and the limits we place on the presence of any $\gamma$-ray pulsars. The limits quoted on both pulsed fraction $A_{\rm UL}$ and pulsed flux $P_{\rm UL}$ are 90% confidence limits corrected for dead time and binning at a frequency of 25 Hz. Upper limits at other confidence limits or frequencies can be determined using the formulae in §3.3.

Table 2 contains the 90% confidence limit upper limits for 25 Hz pulsations from isolated pulsars. Upper limits for $\gamma$-ray pulsations from two known X-ray pulsars are included in Table 2. For these two pulsars we obtained the largest and deepest summed power spectrum and looked for a signal at the known frequency; the upper limits are quoted at the pulsars' known frequencies, not 25 Hz. PSR B0540-693 is a 50 ms pulsar in the LMC discovered in the soft X-ray band with the *Einstein Observatory* (Seward, Harnden &

Helfand 1984) and subsequently detected optically (Middleditch & Pennypacker 1985). The energetics, age, and morphology of PSR B0540-693 are similar to those of the Crab pulsar. We used an ephemeris provided to the OSSE group by J. Taylor (private communication) to estimate a pulse period of 50.39 ms during the OSSE observation (Observation ID 33). PSR B1613-509 is a 69 ms X-ray pulsar in the supernova remnant RCW 103 (Aoki, Dotani, & Mitsuda 1992). As the pulse derivative is not known, we have searched all periods within $\pm 0.400$ ms of the measured period of 69.32 ms (Observation ID 35).

Table 2 also contains the results of searches over a range of periods for non-Doppler shifted pulsations from both known and unknown sources. Known sources which might be expected to show $\gamma$-ray pulsations include the the LMC supernova SN 1987A (Observation IDs 31 & 32), the M81 supernova SN 1993J (Observation IDs 23 & 24), the galactic $\gamma$-ray transient GRO J0422+32 (Nova Per 1992; Observation ID 12), and the pulsars Geminga (Observation ID 30) and PSR B1929+10 (Observation ID 13). Although $\gamma$-ray emission has been detected from all of these sources except PSR B1929+10, none except Geminga show $\gamma$-ray pulsations. Although pulsed high energy $\gamma$-ray emission has been observed from Geminga at its 4.2 Hz pulse frequency ($P$ = 237 ms) by EGRET (Bertsch et al. 1992; Mayer-Hasselwander et al. 1994), it has not been detected by OSSE. Using period folding techniques, which are more sensitive than Fourier searches for sources with known periods, Ulmer & Schroeder (1994a,b) report an upper limit to the pulsed $\gamma$-ray flux of $8 \times 10^{-6}$ $\gamma$ $s^{-1}$ $cm^{-2}$ (50–200 keV) with OSSE, more than order of magnitude fainter than the limit quoted in Table 2.

Note that the count rate reported in Table 2 is the count rate for source plus background. Consequently, the 90% confidence upper limit on the pulsed fraction quoted is that of the source plus background. The pulsed fraction of the source alone is necessarily higher, but is typically unknown. For GRO J0422+32 the source accounts for approximately half of the total count rate (Grove et al. 1992), and hence the pulsed fraction of the source alone is twice the tabulated values. For SN 1987A the source accounts for less than 1% of the total count rate (Kurfess et al. 1992) and for SN 1993J the source also accounts for less than 1% of the total count rate (Leising et al. 1994). PSR B1929+10 has not been detected with OSSE.

We also searched for pulsed emission in fields which are not known to contain a compact $\gamma$-ray source, including fields in the Galactic plane, the Galactic Center, and the LMC. For several Galactic plane fields, we searched for pulsed emission from positions $0.5^\circ$ off axis from the field center, as well as from the offset OSSE detectors being used to monitor the background $5^\circ$ from the target field. No pulsed $\gamma$-ray emission was detected.

Table 3 contains the results of our searches for binary pulsars. Most of the fields

searched for Doppler shifted $\gamma$-ray pulsations did not contain a known source from which a positive signal might be expected. Two exceptions are the fields containing GRO J0422+32 (Observation ID 12) and SN 1993J (Observation ID 23). The binary period of GRO J0422+32 is 5.06 hr (Orosz & Bailyn 1994). A binary pulsar might be expected in SN 1993J from theoretical considerations. Binary pulsars were also searched for in OSSE observations along the Galactic plane and at several epochs. No Doppler shifted $\gamma$-ray pulsations were detected.

## 5. Discussion

We have conducted a sensitive search in the 50–200 keV energy range for pulsed $\gamma$-ray emission from previously unknown and undetected pulsars at frequencies between 2 and 500 Hz ($P$ = 2–500 ms). We have detected none.

Parallel programs have been conducted by both the OSSE and EGRET teams to detect pulsed $\gamma$-ray emission from known radio pulsars. OSSE has observed 18 pulsars, including the 3 detected, and upper limits to the pulsed flux have been derived for the 15 undetected pulsars using the known radio ephemerides (Ulmer & Schroeder 1994a,b; Schroeder et al. 1994). Using data from its all-sky survey, the EGRET team searched for pulsed and unpulsed emission above 100 MeV from 80 known radio pulsars (Thompson et al. 1994; Fierro et al. 1994). Possible detections of pulsed flux from 1 pulsar and unpulsed emission from 5 are reported (Thompson et al. 1994), though some, if not all, of the latter are likely to be chance positional coincidences with EGRET's large error box.

Understanding which pulsars are detectable in $\gamma$-rays provides critical information in constraining the emission mechanisms and geometries for pulsars. The OSSE and EGRET surveys of known pulsars both can be used in this way. The outer gap model (Cheng et al. 1986a,b; Ruderman & Cheng 1988; Chen & Ruderman 1993) predicts that the $\gamma$-ray production efficiency is a function of the pulse period, characteristic age, and viewing and source geometries. Both EGRET (Thompson et al. 1994) and OSSE (Ulmer & Schroeder 1994b) observe correlations which are consistent with this model. In particular, the $\gamma$-ray production efficiency increases with either characteristic age or decreasing rotational energy loss. However, no simple model fits all of the data — for every apparent correlation, there is a counterexample.

The search for new pulsars reported here can be used to place constraints on a different class of pulsars than the known radio pulsars. Our survey is sensitive to pulsars whose radiation peaks in the 50–200 keV range but have not been detected as soft X-ray pulsars (e.g. Ögelman 1994). Their radio emission would need to be undetectable, or their spin

down flux so small ($\dot{E}/D^2 < 10^{34}$ ergs s$^{-1}$ kpc$^{-2}$, where $\dot{E}$ is the spindown luminosity and $D$ is the distance) that they were not chosen for study with pointed OSSE observations (Schroeder et al. 1994). They might be detectable as EGRET sources, but are too faint in the EGRET band for their pulsed nature to be discovered.

Let us take PSR B1509-58 as a prototype for this class of pulsar. PSR B1509-58 has weak radio emission, detectable soft X-ray emission, no detectable emission at $> 100$ MeV, a large pulse period derivative, and a distance of 4.4 kpc (Matz et al. 1994, and references therein). However it is easily detectable by OSSE and has a pulsed flux of $F_{1509} = 0.6 \times 10^{-3}$ $\gamma$ s$^{-1}$ cm$^{-2}$ in the 50–200 keV energy range of OSSE (Matz et al.). We searched 35 fields for isolated pulsars similar to PSR B1509-58 (Table 2). The area searched in each field is that part of the sky for which pulsed signals are properly corrected for motion of the satellite; this is significantly less than the $\sim$40 square degree OSSE field-of-view. We estimate that coherent signals are recovered from a $\sim$4 square degrees area about the pointing direction; this area is rectangular with the long side pointing towards the CGRO orbital pole. The volume in which we are sensitive to pulsars similar to PSR B1509-58 is then

$$V = \frac{1}{3} \frac{F_{1509}}{F_{\rm UL}} D_{1509}^3 \, \Omega \,, \tag{10}$$

where $F_{\rm UL}$ is the pulsed flux upper limit given in the last column of Table 2 and $\Omega$ is the angular area searched per field in square radians.

The total volume searched for pulsars similar to PSR B1509-58, with periods between 2 and 500 ms, is 1.8 kpc$^3$. Since none were detected, we set a rough upper limit of one PSR B1509-58-like pulsar per 1.8 kpc$^3$. This would translate to an upper limit of perhaps 125 such pulsars in the Galaxy. We see that pulsars similar to PSR B1509-58 are rather rare and form an extremely small fraction of the estimated 350,000 active pulsars in the Galaxy (Lyne & Graham-Smith 1990).

For isolated pulsars like PSR B1509-58, some increase in sensitivity will be obtained by using larger FFTs. We will continue to take advantage of the increased memory available in the CM-200 to improve the sensitivity of our searches. More sensitive searches will also be possible on NRL's CM-5, which is several times faster than the CM-200 and has 32 Gbyte of memory.

The sensitivity of the searches for binary pulsars is principally limited by the signal-to-noise ratio of the data. It is not possible to sum incoherently quadratically shifted power spectra without decreasing the significance of any possible signal in the power spectrum. Longer FFTs do not solve the problem because the data segment will be an appreciable fraction of the binary orbit, and the quadratic transform will no longer recover the coherent signal in a single channel of the power spectrum. An increase in sensitivity can

only come from larger source count rates, which require larger effective areas in the $\gamma$-ray detector.

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Table 1. Log of OSSE Observations Analyzed

| Obs ID[a] | Target[b] | Viewing Period[c] | Galactic long | Galactic lat | Celestial RA (J2000) | Celestial Dec (J2000) | Energy[d] (keV) | Num Det[e] |
|---|---|---|---|---|---|---|---|---|
| 1 | Galactic Center | 16 | 0.00 | 0.00 | 266.40 | -28.94 | 40–150 | 1 |
| 2 | Galactic Center | 24.0 | 0.00 | 0.00 | 266.40 | -28.94 | 40–165 | 1 |
| 3 | G Plane 5 (off axis) | 24.5 | 4.87 | 0.43 | 268.79 | -24.53 | 38–87 | 2[f] |
| 4 | G Plane 5 (offset) | 24.5 | 4.89 | -4.60 | 273.67 | -26.98 | 38–87 | 1 |
| 5 | G Plane 5 | 24.5 | 5.13 | -0.00 | 269.34 | -24.53 | 38–87 | 2 |
| 6 | G Plane 5 (offset) | 24.5 | 5.37 | 4.54 | 265.23 | -21.99 | 38–87 | 1 |
| 7 | G Plane 5 (off axis) | 24.5 | 5.38 | -0.44 | 269.89 | -24.53 | 38–87 | 2[f] |
| 8 | G Plane 25 (offset) | 13.0 | 24.97 | -10.02 | 288.29 | -11.58 | 65–157 | 1 |
| 9 | G Plane 25 | 13.0 | 24.98 | -0.02 | 279.23 | -7.08 | 65–157 | 2 |
| 10 | G Plane 25 (offset) | 13.0 | 24.98 | 9.98 | 270.35 | -2.42 | 65–157 | 1 |
| 11 | NGC 6814 | 208 | 29.32 | -15.98 | 295.63 | -10.34 | 70–152 | 2 |
| 12 | GRO J0422+32 | 37,39 | 165.88 | -11.91 | 65.43 | 32.91 | 40–170 | 2 |
| 13 | PSR B1929+10 | 18 | 47.38 | -3.89 | 293.06 | 10.99 | 30–343 | 4 |
| 14 | G Plane 58.1 (off axis) | 19 | 57.67 | 0.47 | 294.28 | 22.10 | 78–164 | 2[f] |
| 15 | G Plane 58.1 (offset) | 19 | 58.14 | -10.02 | 304.09 | 17.09 | 78–164 | 1 |

Table 1—Continued

| Obs ID[a] | Target[b] | Viewing Period[c] | Galactic long | Galactic lat | Celestial RA (J2000) | Celestial Dec (J2000) | Energy[d] (keV) | Num Det[e] |
|---|---|---|---|---|---|---|---|---|
| 16 | G Plane 58.1 | 19 | 58.14 | -0.03 | 295.00 | 22.26 | 78–164 | 2 |
| 17 | G Plane 58.1 (offset) | 19 | 58.15 | 9.97 | 285.25 | 26.90 | 78–164 | 1 |
| 18 | G Plane 58.1 (off axis) | 19 | 58.61 | -0.53 | 295.72 | 22.42 | 78–164 | 2[f] |
| 19 | Cyg X-1 | 15 | 71.34 | 3.07 | 299.59 | 35.21 | 40–135 | 1 |
| 20 | Cas A (off axis) | 34 | 110.92 | -2.46 | 349.60 | 58.22 | 77–175 | 2[f] |
| 21 | Cas A | 34 | 111.72 | -2.12 | 350.81 | 58.82 | 77–175 | 2 |
| 22 | Cas A (off axis) | 34 | 112.52 | -1.77 | 352.06 | 59.41 | 77–175 | 2[f] |
| 23 | SN 1993J | 227 | 142.12 | 40.94 | 148.94 | 69.03 | 48–175 | 2 |
| 24 | SN 1993J | 218 | 142.15 | 40.91 | 148.85 | 69.02 | 70–152 | 2 |
| 25 | 3C 111 (off axis) | 4 | 161.40 | -9.24 | 63.97 | 37.92 | 65–157 | 2[f] |
| 26 | 3C 111 | 4 | 161.71 | -8.81 | 64.62 | 38.01 | 65–157 | 2 |
| 27 | 3C 111 (off axis) | 4 | 162.00 | -8.39 | 65.27 | 38.10 | 65–157 | 2[f] |
| 28 | MCG +8-11-11 (off axis) | 222 | 165.48 | 9.95 | 87.97 | 46.43 | 70–152 | 2[f] |
| 29 | MCG +8-11-11 | 222 | 165.74 | 10.43 | 88.76 | 46.44 | 70–152 | 2 |
| 30 | Geminga | 34 | 195.09 | 4.27 | 98.46 | 17.81 | 77–175 | 2 |

Table 1—Continued

| Obs ID[a] | Target[b] | Viewing Period[c] | Galactic long | Galactic lat | Celestial RA (J2000) | Celestial Dec (J2000) | Energy[d] (keV) | Num Det[e] |
|---|---|---|---|---|---|---|---|---|
| 31 | SN 1987A | 6 | 279.70 | -31.94 | 83.86 | -69.27 | 60–210 | 2 |
| 32 | SN 1987A | 29 | 279.70 | -31.94 | 83.86 | -69.27 | 60–210 | 2 |
| 33 | PSR B0540-693 | 6 | 279.72 | -31.52 | 85.05 | -69.33 | 80–210 | 2[g] |
| 34 | $\eta$ Car | 14 | 288.04 | -0.73 | 161.95 | -59.98 | 50–165 | 2 |
| 35 | PSR B1613-509 | 9.0 | 332.42 | -0.36 | 244.38 | -51.03 | 40–190 | 1[h] |

[a]Arbitrary observation identification number for this data.

[b]Target of OSSE observation; "off axis" indicates data were barycenter corrected for a position 0.5° from the target, and "offset" indicates data were taken from a detector observing the background ~5° from the target.

[c]Compton Gamma Ray Observatory viewing period.

[d]Energy range of counts accepted by pulse height discriminators.

[e]Number of OSSE detectors used to gather data; effective area of each detector is ~470 cm$^2$ but is dependent on the energy range of the discriminators.

[f]Observation is 0.5° off axis; detector effective area is reduced by ~5%.

[g]Pulsar is 0.4° off axis; detector effective area is reduced by ~11%.

[h]Pulsar is 7.6° off axis; detector effective area is reduced by ~60%.

Table 2. Pulse Limits for Isolated Pulsars

| Obs ID[a] | Obs Date[b] (TJD) | $N$ (bins) | $\tau$ (ms) | $M$ (FFTs) | count rate (ct $s^{-1}$) | freq range (Hz) | pulse fract[c] (%rms) | pulse flux[d] |
|---|---|---|---|---|---|---|---|---|
| 1 | 8606–8606 | 1 M | 4 | 16 | 129.8 | 2–125 | 0.26 | 0.71 |
| 2 | 8716–8716 | 4 M | 1 | 9 | 137.0 | 2–500 | 0.67 | 1.96 |
| 3 | 8721–8728 | 2 M | 1 | 61 | 169.4 | 2.5–500 | 0.37 | 0.70 |
| 4 | 8721–8728 | 2 M | 1 | 34 | 87.3 | 2–500 | 0.83 | 1.54 |
| 5 | 8721–8728 | 2 M | 1 | 61 | 169.4 | 2.5–500 | 0.37 | 0.67 |
| 5 | 8721–8728 | 64 M | 0.625 | 13 | 168.6 | 14–800 | 0.25 | 0.45 |
| 6 | 8721–8728 | 2 M | 1 | 32 | 87.6 | 2–500 | 0.57 | 1.06 |
| 7 | 8721–8728 | 2 M | 1 | 61 | 169.4 | 2.5–500 | 0.37 | 0.70 |
| 8 | 8560–8567 | 2 M | 1 | 99 | 69.8 | 2 –500 | 0.38 | 0.56 |
| 10 | 8560–8567 | 2 M | 1 | 99 | 72.4 | 2.5–500 | 0.42 | 0.65 |
| 11 | 9020–9027 | 2 M | 1 | 96 | 100.8 | 2–500 | 0.29 | 0.31 |
| 12 | 8858–8866 | 64 M | 0.125 | 21 | 258.9 | 2–4000 | 0.22 | 0.61 |
| 13 | 8631–8644 | 256 k | 8 | 174 | 436.8 | 2–62.5 | 0.11 | 0.26 |
| 14 | 8644–8658 | 2 M | 1 | 157 | 79.1 | 2–500 | 0.28 | 0.25 |
| 15 | 8644–8658 | 2 M | 1 | 160 | 40.4 | 2–500 | 0.40 | 0.34 |

Table 2—Continued

| Obs ID[a] | Obs Date[b] (TJD) | $N$ (bins) | $\tau$ (ms) | $M$ (FFTs) | count rate (ct $s^{-1}$) | freq range (Hz) | pulse fract[c] (%rms) | pulse flux[d] |
|---|---|---|---|---|---|---|---|---|
| 16 | 8644–8658 | 2 M | 1 | 157 | 79.1 | 2–500 | 0.29 | 0.24 |
| 17 | 8644–8658 | 2 M | 1 | 159 | 40.4 | 2–500 | 0.39 | 0.34 |
| 18 | 8644–8658 | 2 M | 1 | 157 | 79.1 | 2–500 | 0.27 | 0.24 |
| 19 | 8593–8593 | 256 k | 4 | 15 | 96.6 | 2–125 | 0.66 | 1.36 |
| 20 | 8819–8840 | 2 M | 1 | 142 | 109.8 | 2–500 | 0.27 | 0.33 |
| 21 | 8819–8840 | 2 M | 1 | 142 | 109.8 | 2–500 | 0.27 | 0.32 |
| 22 | 8819–8840 | 2 M | 1 | 142 | 109.8 | 2–500 | 0.26 | 0.32 |
| 23 | 9167–9185 | 4 M | 0.5 | 160 | 213.4 | 2.5–1000 | 0.18 | 0.41 |
| 24 | 9097–9112 | 4 M | 0.5 | 83 | 101.0 | 2–1000 | 0.30 | 0.32 |
| 25 | 8435–8449 | 2 M | 1 | 155 | 124.4 | 2.5–500 | 0.26 | 0.36 |
| 26 | 8435–8449 | 2 M | 1 | 155 | 124.4 | 2.5–500 | 0.26 | 0.34 |
| 27 | 8435–8449 | 2 M | 1 | 155 | 124.4 | 2.5–500 | 0.26 | 0.36 |
| 28 | 9131–9138 | 2 M | 1 | 21 | 100.5 | 2–500 | 0.34 | 0.38 |
| 29 | 9131–9138 | 2 M | 1 | 37 | 99.9 | 2–500 | 0.41 | 0.44 |
| 30 | 8819–8840 | 256 k | 8 | 153 | 166.3 | 2–62.5 | 0.20 | 0.35 |

Table 2—Continued

| Obs ID[a] | Obs Date[b] (TJD) | $N$ (bins) | $\tau$ (ms) | $M$ (FFTs) | count rate (ct $s^{-1}$) | freq range (Hz) | pulse fract[c] (%rms) | pulse flux[d] |
|---|---|---|---|---|---|---|---|---|
| 31 | 8466–8476 | 32 M | 0.125 | 117 | 184.0 | 2–4000 | 0.21 | 0.42 |
| 32 | 8757–8776 | 8 M | 0.125 | 336 | 144.0 | 2–4000 | 0.23 | 0.35 |
| 33 | 8466–8476 | 2 M | 8 | 54 | 249.0 | 19.84[e] | 0.10 | 0.29 |
| 34 | 8577–8577 | 1 M | 4 | 16 | 120.4 | 2–125 | 0.30 | 0.38 |
| 35 | 8505–8510 | 64 M | 8 | 1 | 113.1 | 14.43[f] | 0.12 | 0.73 |

[a]Arbitrary observation identification number for this data (see Table 1).

[b]TJD (truncated Julian day) = JD − 2440000.

[c]90% confidence limit on pulse fraction.

[d]90% confidence limit on pulse flux in units of $10^{-3}$ $\gamma$ $s^{-1}$ $cm^{-2}$.

[e]Search at known period (50.4 ms) only.

[f]Search at known period (69.3 ms) only.

Table 3. Pulse Limits for Binary Pulsars

| Obs ID[a] | Obs Date[b] (TJD) | $N$ (bins) | $\tau$ (ms) | $N_\alpha$ (trials) | count rate (ct s$^{-1}$) | freq range (Hz) | pulse fract[c] (%rms) | pulse flux[d] |
|---|---|---|---|---|---|---|---|---|
| 1 | 8606.1875 | 1M | 4 | 321 | 129.8 | 2–125 | 1.21 | 3.36 |
| 2 | 8716.5625 | 8M | 0.25 | 1272 | 137.0 | 2–2000 | 2.00 | 5.83 |
| 4 | 8728.3101 | 2M | 1 | 411 | 87.6 | 2–500 | 3.41 | 6.36 |
| 5 | 8726.3779 | 2M | 1 | 411 | 178.5 | 2–500 | 1.81 | 3.44 |
| 6 | 8726.6865 | 2M | 1 | 411 | 88.4 | 2–500 | 2.81 | 5.29 |
| 8 | 8561.3382 | 2M | 1 | 411 | 75.2 | 2–500 | 2.18 | 3.49 |
| 8 | 8564.0472 | 2M | 1 | 411 | 67.9 | 2–500 | 2.23 | 3.23 |
| 8 | 8566.3458 | 2M | 1 | 411 | 77.9 | 2–500 | 2.21 | 3.67 |
| 9 | 8560.8805 | 2M | 1 | 411 | 138.3 | 2–500 | 1.58 | 2.33 |
| 9 | 8562.8055 | 2M | 1 | 411 | 136.8 | 2–500 | 1.53 | 2.22 |
| 9 | 8565.8125 | 2M | 1 | 411 | 134.7 | 2–500 | 1.64 | 2.36 |
| 10 | 8561.7185 | 2M | 1 | 411 | 68.4 | 2–500 | 2.52 | 3.66 |
| 10 | 8564.3060 | 2M | 1 | 411 | 82.1 | 2–500 | 2.43 | 4.25 |
| 10 | 8566.6986 | 2M | 1 | 411 | 72.3 | 2–500 | 2.72 | 4.18 |
| 11 | 9020.7131 | 2M | 1 | 411 | 108.5 | 2–500 | 1.62 | 1.87 |
| 11 | 9022.9435 | 2M | 1 | 411 | 101.5 | 2–500 | 1.57 | 1.70 |
| 11 | 9024.9831 | 2M | 1 | 411 | 101.6 | 2–500 | 1.68 | 1.82 |
| 12 | 8860.1250 | 16M | 0.125 | 2941 | 231.5 | 2–4000 | 1.17 | 2.87 |

Table 3—Continued

| Obs ID[a] | Obs Date[b] (TJD) | $N$ (bins) | $\tau$ (ms) | $N_\alpha$ (trials) | count rate (ct $s^{-1}$) | freq range (Hz) | pulse fract[c] (%rms) | pulse flux[d] |
|---|---|---|---|---|---|---|---|---|
| 13 | 8631.8251 | 256k | 8 | 53 | 420.5 | 2–62.5 | 0.79 | 1.76 |
| 13 | 8636.0170 | 256k | 8 | 53 | 294.0 | 2–62.5 | 0.95 | 1.48 |
| 13 | 8642.1448 | 256k | 8 | 53 | 323.8 | 2–62.5 | 0.97 | 1.67 |
| 15 | 8645.0132 | 2M | 1 | 411 | 41.8 | 2–500 | 2.60 | 2.32 |
| 15 | 8651.0736 | 2M | 1 | 411 | 42.0 | 2–500 | 2.63 | 2.35 |
| 15 | 8658.1045 | 2M | 1 | 411 | 41.9 | 2–500 | 2.64 | 2.36 |
| 16 | 8646.1094 | 2M | 1 | 411 | 87.2 | 2–500 | 1.78 | 1.66 |
| 16 | 8651.0741 | 2M | 1 | 411 | 83.4 | 2–500 | 1.91 | 1.70 |
| 16 | 8658.1051 | 2M | 1 | 411 | 83.2 | 2–500 | 1.86 | 1.64 |
| 17 | 8645.0790 | 2M | 1 | 411 | 43.1 | 2–500 | 2.57 | 2.35 |
| 17 | 8651.0747 | 2M | 1 | 411 | 42.2 | 2–500 | 2.49 | 2.24 |
| 17 | 8658.1058 | 2M | 1 | 411 | 41.6 | 2–500 | 2.61 | 2.31 |
| 19 | 8593.5625 | 256k | 4 | 141 | 99.5 | 2–125 | 1.56 | 3.30 |
| 21 | 8819.7345 | 2M | 1 | 411 | 117.5 | 2–500 | 1.70 | 2.12 |
| 21 | 8828.9643 | 2M | 1 | 411 | 113.9 | 2–500 | 1.75 | 2.12 |
| 21 | 8835.8841 | 2M | 1 | 411 | 109.4 | 2–500 | 1.70 | 1.97 |
| 23 | 9174.1275 | 4M | 0.5 | 821 | 217.3 | 2–1000 | 1.14 | 2.63 |

Table 3—Continued

| Obs ID[a] | Obs Date[b] (TJD) | $N$ (bins) | $\tau$ (ms) | $N_\alpha$ (trials) | count rate (ct $s^{-1}$) | freq range (Hz) | pulse fract[c] (%rms) | pulse flux[d] |
|---|---|---|---|---|---|---|---|---|
| 26 | 8440.0570 | 2M | 1 | 411 | 168.0 | 2–500 | 1.77 | 3.16 |
| 26 | 8446.2802 | 2M | 1 | 411 | 113.8 | 2–500 | 1.70 | 2.05 |
| 26 | 8449.7171 | 2M | 1 | 411 | 121.7 | 2–500 | 1.49 | 1.93 |
| 29 | 9133.0236 | 2M | 1 | 411 | 102.8 | 2–500 | 1.60 | 1.75 |
| 29 | 9133.9125 | 2M | 1 | 411 | 99.6 | 2–500 | 1.62 | 1.72 |
| 29 | 9137.0221 | 2M | 1 | 411 | 101.5 | 2–500 | 1.62 | 1.74 |
| 30 | 8820.0156 | 256k | 8 | 53 | 167.9 | 2–62.5 | 1.26 | 2.25 |
| 30 | 8831.0421 | 256k | 8 | 53 | 169.1 | 2–62.5 | 1.26 | 2.27 |
| 30 | 8838.6022 | 256k | 8 | 53 | 165.2 | 2–62.5 | 1.26 | 2.21 |
| 34 | 8581.6875 | 1M | 4 | 321 | 164.2 | 2–125 | 0.88 | 1.53 |

[a]Arbitrary observation identification number for this data (see Table 1).

[b]TJD (truncated Julian day) = JD − 2440000.

[c]90% confidence limit on pulse fraction.

[d]90% confidence limit on pulse flux in units of $10^{-3}\ \gamma\ s^{-1}\ cm^{-2}$.

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